To Adopt, or Not to Adopt, 'Why' is the Question: A Case for Clean Kiln Technologies in Developing Countries[Ψ]

Sanval Nasim
Assistant Professor of Economics
Lahore University of Management Sciences
sanval.nasim@lums.edu.pk

Faiza Sharif
Professor
Sustainable Development Center
Government College University, Lahore
faizasharif@gcu.edu.pk

Abstract

In this paper, two brick kiln technologies—the Bull's Trench Kiln (BTK) and the Induced Draft Zigzag Kiln (ZZK)—were compared through a transdisciplinary approach by focusing on two questions: do ZZKs tend to be cleaner than BTKs? Will operating ZZKs generate any reasonable economic and social benefits? To answer the first question, stack emission samples were collected and tested from two kilns: a newly constructed ZZK in Punjab, Pakistan and a conventional BTK located close to the ZZK. To address the second question, a cost-benefit analysis of the two types of kiln technologies was conducted using primary data on input and output quantities and prices from the sample kilns. The environmental results show that the ZZK emitted significantly less amount of harmful gases and particulate matter compared to the BTK. The economic analysis demonstrates that ZZKs improve both private and social welfare in monetary terms compared to BTKs. Our findings provide a case for the adoption of ZZKs in developing countries and for environmental policymakers to facilitate the technology transition.

Keywords: Air Pollution; Technology Adoption; Development

[Ψ] Both authors contributed equally to this study.

1. Introduction

Urbanization and infrastructure development have led to a rapid growth of the brick industry in many developing countries. In Pakistan, for example, the brick kiln industry is an important component of industrial output—with over 10 thousand kilns in Punjab province alone—and contributes 1.5 percent to the country's gross domestic product (ICIMOD 2019). However, brick producers in South and Southeast Asia—the largest brick producing region in the world—heavily rely on old and dirty kiln technologies, which are a large source of greenhouse gas emissions and harmful pollutants (Skinder et al. 2014). The problem is particularly egregious in India and Pakistan, which have failed to modernize their conventional kiln technology—the over a century old fixed chimney Bull's trench kiln (BTK)—and experience exceptionally dangerous levels of particulate matter. The introduction of new kiln technologies such as the induced draft zigzag kiln (ZZK) presents policymakers in developing countries a possible opportunity to improve ambient air quality, mitigate climate change, and in turn reduce social costs.

Evidence indicates that emissions in developing countries are increasing at an alarming rate and that levels of pollutants exceed the thresholds prescribed by the World Health Organization (WHO) (Khan et al. 2011; Lodhi 2006; Colbeck et al. 2009). During a menacing smog episode in November 2017, the average concentration of $PM_{2.5}$ in Lahore was 1077 micrograms per cubic meter ($\mu g/m^3$)—almost 200 times higher than WHO's safe limit of 6 $\mu g/m^3$ (EPD 2017). Exposure to such toxic levels of particulate matter increases the incidence of cancer and can lead to severe cardiovascular and respiratory illnesses such as ischemia, myocardial infarction, asthma, and bronchitis (Kamal et al. 2014; Dominici et al. 2006; Brook et al. 2004). According to WHO estimates, about 135,000 people in Pakistan died in 2015 as a result of exposure to hazardous levels of $PM_{2.5}$ (HEI 2017).

Deteriorated air quality also carries serious non-health implications. Visibly poor air quality increases the risk of traffic accidents and encourages people to spend more time indoors, leading to high absenteeism at work and in schools (Sager 2016; Gilliland et al. 2001). Moreover, the exposure of plants and crops to air pollutants causes foliar damage and stunts growth by affecting their ability to photosynthesize (Adrees et al. 2016). The high indirect costs of emissions, in addition to their direct impacts, make it all the more important for environmental authorities in developing countries to engage in concrete actions to reduce emissions and improve air quality.

Spread widely across South Asia, BTKs use coal as a primary fuel source and are a significant source of greenhouse gas emissions and harmful particulate matter, including $PM_{2.5}$, sulfur dioxide (SO_2), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO_x), methane (CH_4), and black carbon (Skinder et al. 2014; Croitoru and Sarraf 2012). At times, kiln operators burn cheap waste materials such as discarded tires, plastics, and garbage as fuel, resulting in the release of toxic byproducts in the surrounding environment (Sanjel et al. 2016; Tahir et al. 2010).

Recent inquiries on kilns in South Asia demonstrate the seriousness of the problem: annual CO_2, CO, and $PM_{2.5}$ emissions from kilns in the region range between 120 – 127 megatons (mt), 2.5 – 3.9 mt, and 0.19 – 0.94 mt, respectively (Weyant et al. 2014; Rajarathnam et al. 2014). Kilns are also a source of carcinogens such as polycyclic aromatic hydrocarbons and volatile organic compounds (Chen et al. 2017; Stockwell et al. 2016; Zavala et al. 2018)—kiln workers have a high risk of exposure to such carcinogens through dermal contact and inhalation. Moreover, the disposal of kiln ash, which contains toxic heavy metals, can contaminate agricultural land and produce (Ismail et al. 2012; Adrees et al. 2016; Mondal et al. 2017).

ZZK is a relatively cleaner alternative to the conventional BTK. Recent experiences from India, Bangladesh, and Nepal—where a large number of kiln owners have quickly taken up ZZK technology—suggest that ZZKs combust coal more efficiently than BTKs, leading to relatively lower emissions of certain pollutants (Weyant et al. 2014; Rajarathnam et al. 2014; Stockwell et al. 2016; Jayarathne et al. 2018; Tehzeeb and Bhuiyan 2014). ZZKs offer a possible opportunity to improve ambient air quality and thereby inducing better social outcomes such as lower healthcare expenditures, higher crop yields, less material damage, and higher attendance rates at schools and workplaces.

ZZKs also have the potential to generate considerable profit margins if properly operated. Owing to the even and consistent distribution of heat through their chambers and the efficient consumption of coal, ZZKs have the potential to produce 25 percent more high-quality bricks and to use over 30 percent less fuel (primarily coal) compared to BTKs (Maithel et al. 2014). The production of more high-quality bricks and lower input costs translate into higher net private benefits for ZZK owners.

Another private financial incentive to substitute ZZKs for BTKs is the low capital investment required to make the technology shift. ZZK technology can be integrated into existing BTK infrastructure through a fairly straightforward process: owners must install an electric fan in the flue, which artificially induces and regulates draft through the kiln, and stack bricks in a zigzag arrangement within the kiln (Rajarathnam et al. 2014; Weyant et al. 2014). If investors can recover their startup costs in a reasonably short period of time, installing new ZZKs could be financially prudent.

However, the evidence on the environmental and social benefits of ZZKs over BTKs remains sparse and contested. In this paper, a transdisciplinary approach was taken to contribute to the growing literature on kiln technologies by focusing on two questions: do ZZKs tend to be cleaner than BTKs? Will operating ZZKs generate any reasonable economic and social benefits? To answer the first question, stack emission samples were collected and tested from two kilns: a newly constructed ZZK in Punjab, Pakistan and a conventional BTK located about three kilometers from the ZZK. The enterprising owner recently setup the ZZK after procuring design plans from the International Center for Integrated Mountain Development (ICIMOD) in Nepal. This was the only operational ZZK in Punjab until the collection of the data and provides a benchmark for comparison with conventional kilns in the province. To address the second question, a cost-benefit analysis of the two types of kiln technologies was conducted using primary data on input and output quantities and prices from the sampled kilns. An overview of the two kiln technologies is provided in the Appendix.

However, the analysis and results come with a few caveats. Given the study's limited budget and the fact that there was only one functional ZZK in Punjab when the study was conducted, only two kilns—one BTK and one ZZK—could be analyzed. The results from the limited sample size are not representative of the larger sample of kilns and thus cannot be generalized to all BTKs and ZZKs in the region. Nonetheless, the analysis provides a snapshot of the environmental and economic differences between BTKs and ZZKs in Punjab, which policymakers can use to inform a more comprehensive study and policy actions on kilns in the province. Moreover, this is the first study to quantify the difference in the social benefits between BTKs and ZZKs using present-value calculations—this provides policymakers a better criterion to assess the long-term social costs and benefits of investments in each type of kiln.

The paper is structured as follows: Section 2 provides the environmental analysis, including the methodology for emission monitoring and the results. Section 3 presents the economic analysis. Section 4 concludes with a set of limitations and recommendations.

2. Environmental Analysis

2.1. Methodology

2.1.1. Site Selection

Emission samples were collected from a BTK and a ZZK located on the outskirts of Lahore, the capital of Pakistan's Punjab province. At the time of data collection, the sampled ZZK was the only functional kiln of its type in Punjab and constructed six months prior. To reduce spatial heterogeneity and to control for factors such as weather and output and input prices, which might vary over space, the sampled kilns were required to be within a reasonable distance of each other. The Environment Protection Department, Punjab (EPD) helped locate a BTK for emission monitoring in the vicinity (3.2 kilometers) of the ZZK. Another factor behind the selection of the kilns was the comparability of their fuel type—both kilns used coal as the main fuel. Photographs of the two kilns are included in the Appendix (Figure A1).

Kilns are usually categorized as "intermittent" or "continuous" and the sampled BTK and ZZK fall in the latter category. In a continuous kiln, the fire is never extinguished. The sampled BTK relies on natural draft to sustain the fire while the ZZK has an electric fan in the vent to artificially induce and regulate a draft through its chambers. Each kiln is also a major source of emissions in their immediate vicinity—other sources include motor vehicles and agricultural activity. Some of the production and monitoring features of the sampled kilns are provided in Table 1.

Table 1: Production, monitoring and other features of the sampled kilns

Parameters	**BTK**	**ZZK**
Date	05-04-18	26-04-18
Time	3:30 PM	2:50 PM
Site	Parvez Akhtar Bricks	J.P Bannu Ikram Bricks
Sampling probe	¾ inch (PG 350E) ½ inch (PEM-SMS4)	¾ inch (PG 350E) ½ inch (Apex-572)
Fuel consumption per unit time	200-230 kg/h	210-250 kg/h
Fuel consumption for the monitoring time	209 kg/h	230 kg/h
Number of bricks produced	~35,550 bricks/day	~50,000 bricks/day
Bricks produced in monitoring time	35,552 bricks/day	49,920 bricks/day
Location	31° 15.007 N 74° 13.937 E	31° 15.618 N 74° 15.859 E
Stack temperature	$80^{\circ}C$	$65^{\circ}C$
Ambient temperature	$35^{\circ}C$	$41^{\circ}C$
Stack height	21.95 m	25 m
Fuel used	Coal (100 percent)	Coal (99 percent), Rice husk and poultry waste (1 percent)

2.1.2. Fuel Sources and Analysis

Coal is the main fuel source of the sampled kilns. The BTK uses a mixture of two types of coal: one from Hyderabad and the other from Balochistan, with each comprising 75 percent and 25 percent, respectively, of the mixture. Coal from Balochistan is generally better quality—in terms of higher heat production capacity—and is therefore more expensive than coal from Hyderabad. The coal at the ZZK is entirely from Balochistan. The ZZK uses (i) rice husk; (ii) coal and rice husk mixture, or (iii) rice husk reused from poultry waste as a fuel for warming up newly opened fuel holes.

In the ZZK, workers continuously feed coal through 14 rows of fuel holes in the firing zone, with a 35-hour feeding time for each row—it takes 35 hours of firing to bake 5,200 bricks stacked under each row. Every three hours, workers close a row of fuel holes that has completed its 35-hour firing cycle and open a new row at the opposite end of the feeding zone. The ZZK bakes around 72,800 bricks in this 35-hour cycle—equivalent to 50,000 bricks daily. Fuel feeding in the BTK is divided into fuel feeding (F) and non-feeding (NF) cycles (Figure 1). Workers add coal through a row of feeding holes in intervals of approximately 15 minutes with a break of 20-30 minutes between each feeding cycle. The BTK produces 35,550 bricks daily through this process.

To account for diurnal fuel feeding variation and to cover many fuel feeding and non-feeding cycles, fuel consumption rate during the experiment was recorded by (i) measuring the quantity of fuel taken by the fuel feeding spoon and the rate of fuel feeding during the emission monitoring period; and (ii) repeating the process over a 24-hour period at the BTK and for a 35-hour firing cycle at the ZZK. Fuel samples from each kiln were collected and examined using proximate and ultimate analysis. Calorific value, moisture content, carbon, nitrogen, sulphur, hydrogen, volatile matter and ash contents were determined. Proximate analysis was carried out using elementar vario MICRO cube elemental analyzer.

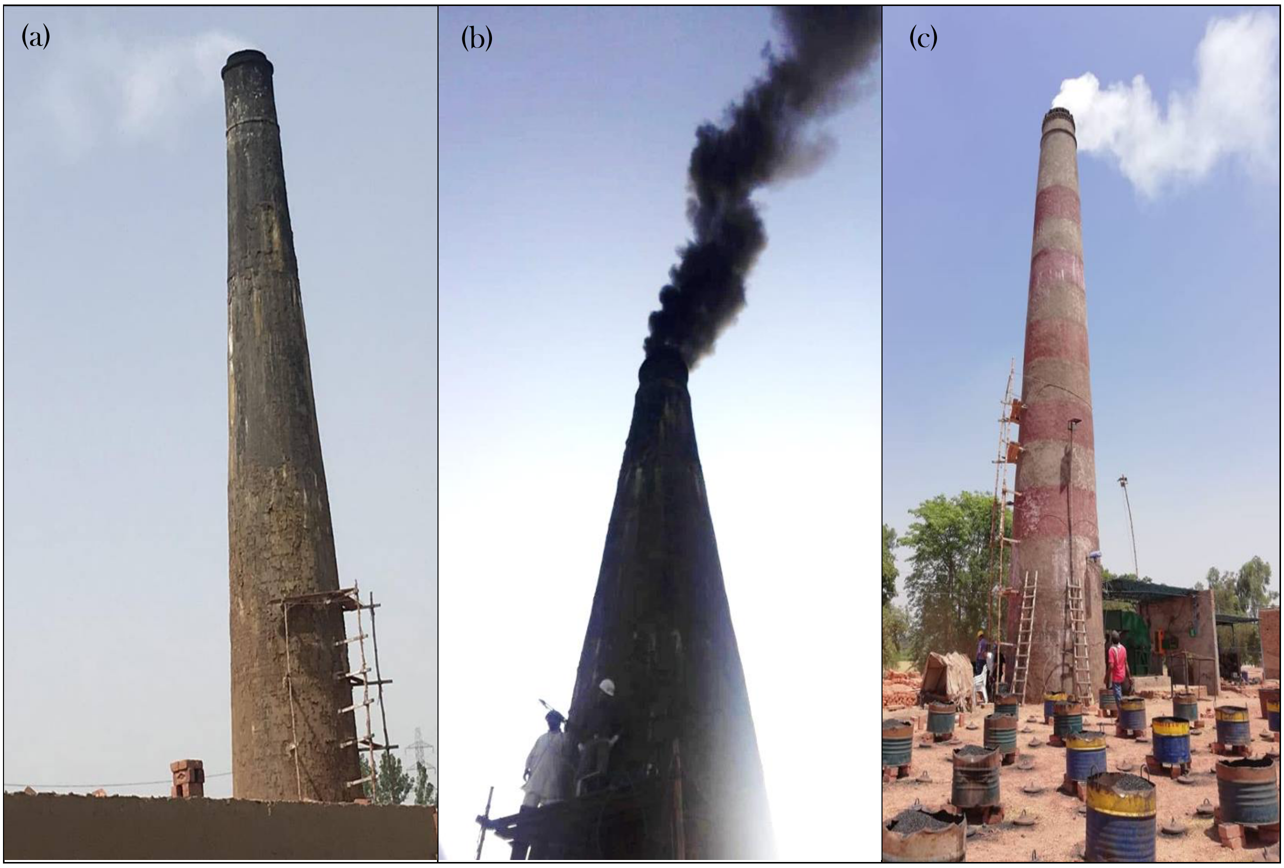

Figure 1: Stack emission sampling of: (a) BTK during non-feeding cycle; (b) BTK during feeding cycle; and (c) ZZK.

2.1.3. Emission Sampling

Stack flow method was used to monitor gaseous (CO_2, CO, NO_x, SO_2) and particulate matter (PM) emissions at both types of kilns. Temporary wooden scaffolding was prepared along the side of the stack for placing equipment and for technicians to reach the sampling point. Sampling was carried out at stack concentrations at a height of 10 m at the BTK and at 12 m at the ZZK because of the difference in their stack heights. Representative PM samples were obtained in an isokinetic manner as given by the US EPA methods of particulate matter monitoring (US EPA Method 17). The stack gas velocity (m/s) was determined by taking into account the S-type Pitot tube coefficient, absolute stack gas temperature, stack gas velocity pressure head (ΔP) and absolute gas pressure (US EPA Method 2). The stack flow rate was calculated by using the stack velocity and the stack cross-sectional area. Isokinetic sampling of particulate matter at the BTK was carried out using PEM-SMS4 assembly while at the ZZK particulate matter monitoring was conducted using Apex-572. PM monitoring was carried out for 25 minutes at the ZZK and for 15 minutes each during the two feeding cycles and the two non-feeding cycles at the BTK. PM was measured gravimetrically after being collected in glass fiber filters for the PEM-SMS4 assembly at the BTK and in glass fiber thimbles for the Apex-572 assembly at the ZZK. The manometer of the PM assemblies recorded the ΔP values.

Real time monitoring of gaseous emissions at both kilns was carried using Horiba PG-350E. The emissions monitoring at the ZZK (continuous feeding) was for a period of 1 hour. Two feeding cycles and two non-feeding cycles at the BTK were monitored—the total feeding and non-feeding monitoring times were 30 minutes and 45 minutes, respectively. The pre- and post-field calibrations of the Horiba PG-350E were carried out in the laboratory with the help of standard gases. For reporting of stack gas concentrations, averages of 15-minute monitoring periods were calculated for the ZZK and the non-feeding cycle of the BTK. This generated four and three observations of the average stack gas concentrations for the ZZK and BTK (non-feeding), respectively. Owing to the comparatively short duration of the BTK feeding cycle, the stack gas concentrations for this cycle were averaged over five minutes to generate a total of six observations. Flue gas concentrations are reported at $25°C$ and 1 atm. Fuel consumption rate was recorded during the monitoring period as described earlier in Section 2.1.2.

2.1.4. Emission Factors

Emission factors were calculated for each kiln to allow comparison of the kilns with each other and with kilns of different sizes, technologies and fuel types. Researchers often use data on emission factors from individual kilns in a country to estimate the emissions of its entire brick industry—information which governments can add to their climate inventories. Two types of emission factors were calculated for each kiln: fuel mass-based and energy-based. The fuel mass-based emission factor measures the emission of a pollutant per unit of the mass of fuel consumed while the energy-based emission factor shows the emission of a pollutant per unit of energy consumed. These were derived from the emission rate and the fuel consumption rate.

The emission rate ER in g/h is (Rajarathnam et al. 2014):

(1) $$ER = 0.001 \times S \times Q_s$$

where S is the stack concentration in mg/m^3 (a weighted average of the stack concentrations of the feeding and non-feeding periods was used for the BTK) and Q_s is the flowrate of flue gases in m^3/h. Time-weighted averages of the stack concentrations of the feeding and non-feeding periods were used for the BTK, considering a 15-minute average feeding cycle and a 30-minute average non-feeding cycle—the measurements are presented in Table A1 of the Appendix.

The fuel mass-based emission factor EF_m g/kg is:

(2) $$EF_m = \frac{ER}{F}$$

where F is the rate of fuel consumption in kg/h.

The energy-based emission factor EF_e in g/MJ is:

(3) $$EF_e = \frac{EF_m}{EC}$$

where EC is the energy content of fuel in MJ/kg.

2.2. Results

2.2.1. Fuel Analysis

Table 2 presents the results of the proximate and ultimate analyses of the fuel samples collected from the BTK and the ZZK. The ZZK uses coal from Balochistan while the BTK uses a mixture of coal from Hyderabad and Balochistan in a three to one proportion. The results of the proximate analysis show that the gross calorific value (GCV), measured in megajoules per kilogram (MJ/kg), of Balochistan coal (26.78 MJ/kg) is almost 50 percent higher than the GCV of Hyderabad coal (18.59 MJ/kg). The Hyderabad-Balochistan coal mixture at the BTK has a GCV of 23.13 MJ/kg. The BTK owners use the coal mixture to reduce costs since the coal from Balochistan costs considerably more than the coal from Hyderabad— $Rs.$ 14,000 per ton versus $Rs.$ 9,000 per ton. However, mixing the two varieties of coal also lowers the energy content of the mixture relative to the energy content of Balochistan coal, reducing the number of bricks fired per ton of fuel. GCV values of both fresh and poultry reused rice husk samples were lowest among all the samples because of their biomass composition. Rice husk comprised only one percent of the total fuel used at the ZZK and served to increase the temperature of the newly opened fuel holes. Volatile matter was highest for poultry reused rice husk followed by fresh rice husk and the Balochistan-Hyderabad coal mix.

All the coal samples have high sulfur content (2.75-6.26 percent) while the rice husk samples have a comparatively lower sulfur content (0.87 percent for fresh husk and 0.70 percent for poultry reused). Nitrogen content for the biomass fuels is higher compared to the coal samples. Its value is highest for the poultry reused rice husk—since it contained poultry waste and feathers—followed by the fresh rice husk. The BTK Balochistan-Hyderabad coal mix has the lowest nitrogen content. The fuel consumption rate is 0.14 kg/fired brick for the BTK and 0.11 kg/fired brick for the ZZK.

2.2.2. Emission Factors

The results of the stack gaseous and PM concentrations are provided in the Appendix (Section A2 and Figure A2). Table 3 presents the energy-based and the fuel-based emission factors for each type of emission from the ZZK and the BTK. These normalizations provide a more consistent comparison of the emissions of the two kilns. The BTK has considerably higher emission factors for all emissions except NO_x compared to the ZZK. The BTK's emission factors (energy-based) for SO_2, CO, CO_2 and PM are 31, 7, 3 and 48 times, respectively, those of the ZZK—the ratios of the fuel mass-based emission factors of these emissions also followed a similar trend.

Table 4 compares the fuel mass-based emission factors (g/kg) measured in this study with those calculated in previous studies. The value of the fuel mass-based PM emission factor for the ZZK in this study (1.01 g/kg) is comparable to the value in Weyant et al. (2014) but 3 times and 15 times lower than the values in Nepal et al. (2019) and Stockwell at el. (2016), respectively. Compared to values in Nepal et al. (2019) and Stockwell at el. (2016), the value of the fuel mass-based SO_2 emission factor for the ZZK in this study is 1.6 and 3 times lower, respectively—coal was the primary fuel in these three studies. However, these values are considerably higher than those for traditional fixed, campaign and MK2 (Marquez Kiln) kilns—which used biomass as the main fuel—in Zavala et al. (2018). The values of the fuel mass-based emission factors for CO, CO_2 and NO_x for the ZZK in this study are comparable to the values reported in previous studies. The values of the fuel mass-based emission factors for the BTK in the current study are considerably higher than the values reported for the BTKs in Nepal et al. (2019) and Weyant et al. (2014).

Table 5 compares the energy-based emission factors (g/MJ) across studies. The energy-based SO_2 emission factor for the BTK in this study is much higher than the values for all kiln types in Rajarathnam et al. (2014) and Zavala et al. (2018)—these kilns used coal and biomass as the primary fuel. The value of the energy-based PM emission factor for the ZZK in this study is lower compared to the values for the ZZKs and other kiln types in Rajarathnam et al. (2014) and Zavala et al. (2018). The values of the energy-based SO_2, CO and CO_2 emission factors for the ZZK in this study is comparable to values reported in previous studies.

Kilns which used wood and other biomass as the main fuel have lower values of the energy-based SO_2 emission factor compared to kilns which used coal as the main fuel because of the relatively higher sulfur content of coal. This value for the ZZK in this study is comparable to the value reported for the ZZK in Rajarathnam et al. (2014). This is despite the fact that the coal used in the current study has a higher sulfur content than the three ZZKs in Rajarathnam et al. (2014)—5.6 percent versus 0.29, 0.56 and 2.49 percent. A possible reason why the energy-based SO_2 emission factors are similar is the higher GCV of the coal used in the ZZK in this study compared to the ZZKs in Rajarathnam et al. (2014)—6397 $kcal/kg$ versus 4391 $kcal/kg$, 4717 $kcal/kg$ and 6209 $kcal/kg$.

Table 2: Proximate and ultimate analyses of fuel samples

Fuel Samples	Total Moisture	Ash	VM	GCV		Nitrogen	Carbon	Sulphur	Hydrogen
	Percent			$(kcal/kg)$	(MJ/kg)	Percent			
ZZK rice husk	7	16	64	3758	15.73	4.97	40.38	0.87	5.05
ZZK Balochistan coal-rice husk mix	5	30	33	5440	22.761	1.06	67.56	6.26	5.31
BTK coal (Balochistan-Hyderabad mix)	10	21	45.90	5524	23.13	0.86	50.63	5.95	4.38
ZZK rice husk (poultry waste)	11	18	87.89	3647	15.27	7.14	34.47	0.70	5.34
Balochistan coal	3.88	13.59	38.80	6397	26.78	1.17	68.52	5.60	5.25
Hyderabad coal	6.89	11.53	30.75	4441	18.59	1.07	58.13	2.75	5.74

Table 3: Emission rates and energy and fuel-based emission factors

	Energy Content-Based Emission Factor (g/MJ)		Fuel Unit Mass-Based Emission Factor (g/kg)		Emission Rate (g/h)	
Kiln Type	ZZK	BTK	ZZK	BTK	ZZK	BTK
SO_2	0.298	9.20	7.97	213	1833	44492
CO	1.04	7.24	27.97	168	6432	35023
NO_x	0.067	0.061	1.80	1.42	414	297
CO_2	106	341	2836	7891	652251	1649172
PM	0.038	1.83	1.01	42.22	233	8823

Table 4: Comparison of fuel mass-based emission factors (g/kg) across studies

	Zavala et al. (2018)			Stockwell et al. (2016) and Jayarathne et al. (2017)		Weyant et al. (2014)			Nepal et al. (2019)		Current Study	
Kiln Type	**MK2**	**Traditional campaign**	**Traditional fixed**	**Clamp**	**ZZK**	**BTK**	**NZZK**	**ZZK**	**BTK**	**ZZK**	**BTK**	**ZZK**
Fuel Type	**Wood**	**Wood**	**Wood, diesel and sawdust**	**Coal and hardwood**	**Coal and bagasse**	**Coal, wood and others**	**Coal, wood and others**	**Coal**	**Coal, rice husk and others**	**Coal and rice husk**	**Coal**	**Coal**
SO_2	1	0.27	0.13	13	12.7	-	-	-	22	24	299	7.97
CO	44.4	50.5	105.2	70.9	10.1	26.4 - 53.8	6.9 - 15.0	19.7 - 32.5	-	-	227	27.97
NO_2[a]	1.7	0.93	1.01	0.297	0.081	-	-	-	-	-	1.47	1.8
CO_2	1583	1527	1668	2102	2620	1963-2597	1965-2099	1831-2104	1633	1981	8453	2836
PM[b]	1.94	4.62	1.32	10.7	15.1	1.7 - 4.4	0.5 - 3.8	0.6 - 1.2	3.8	3.1	42.22	1.01

[a] The current study measured NO_x;
[b] PM measured in Zavala et al. (2018), Jayarathne et al. (2018) and Nepal et al. (2019) was $PM_{2.5}$;
BTK = Fixed chimney Bull's trench kiln; ZZK = Induced draft zigzag kiln; MK2 = Marquez kiln: NZZK = Natural draft zigzag kiln.

Table 5: Comparison of fuel energy-based emission factors (g/MJ) across studies

	Zavala et al. (2018)			Rajarathnam et al. (2014), I = India and V = Vietnam							Current Study	
Kiln Type	**MK2**	**Traditional campaign**	**Traditional fixed**	**BTK (I)**	**NZZK (I)**	**ZZK (I)**	**VSBK (I)**	**DDK (I)**	**VSBK (V)**	**Tunnel Kiln (V)**	**BTK**	**ZZK**
Fuel Type	**Wood**	**Wood**	**Wood, diesel and sawdust**	**Coal, wood and others**	**Coal, wood and others**	**Coal**	**Coal**	**Wood**	**Coal**	**Coal**	**Coal**	**Coal**
SO_2	0.058	0.016	0.007	0.39	0.06	0.23	0.11	< 0.1	1.78	0.49	9.20	0.298
CO	2.57	2.94	5.56	2.96	0.32	1.96	4.39	5.17	2.93	1.56	7.24	1.04
NO_2	-	-	-	-	-	-	-	-	-	-	0.061	0.067
CO_2	91.4	88.9	88.1	140	113	92	126	181	146	109	341	106
PM^a	0.11	0.27	0.07	0.66	0.21	0.23	0.1	0.54	0.22	0.21	1.83	0.038

[a] PM measured in Zavala et al. (2018) was $PM_{2.5}$;
DDK = Down draft kiln; BTK = Fixed chimney Bull's trench kiln; ZZK = Induced draft zigzag kiln; MK2 = Marquez kiln; NZZK = Natural draft zigzag kiln, VSBK = Vertical shaft brick kiln

3. Economic Analysis

Below is a comparison of the private and social benefits and costs of the sampled ZZK and BTK. The values for the analysis are based on data available up until the time the fieldwork was conducted—approximately two months of data—and on the owners' expectations of the future prices of inputs and output. The financial data was acquired through infield interviews with the managers of the sampled kilns. Owing to privacy concerns, the managers did not share the written financial records.

3.1. Private Costs

The startup capital costs for both the BTK and the ZZK comprise the down payment for land lease, advanced labor wages, and construction and equipment costs. Most kiln owners in Punjab construct kilns on leased land with contracts that include a down payment in the first year. They also hire the bulk of the labor by paying wages for a fixed number of years in advance—the advance payment is a loan that workers repay by working at the kilns for a predetermined period (Malik 2016). Construction costs include expenditures on material and labor required to erect the kilns.

Figure 2 shows the total startup capital costs in Rupees ($Rs.$) of the two sampled kilns. The ZZK's initial investment is $Rs.$ 9 million higher than the initial investment for the BTK. The ZZK has higher land and labor costs compared to the BTK since it requires a larger area to accommodate its wide chimney and it employs more workers. Both kilns require a tubewell for pumping water while the ZZK requires additional equipment, including an electric fan, electricity connection (with a transformer), generator, and coal crusher, which drives up its initial investment. The equipment costs are heterogenous (not consistent across kilns) since not all kilns require a tubewell or a coal crusher. However, down payment for land, advanced wages, and construction costs are usually consistent across kilns.

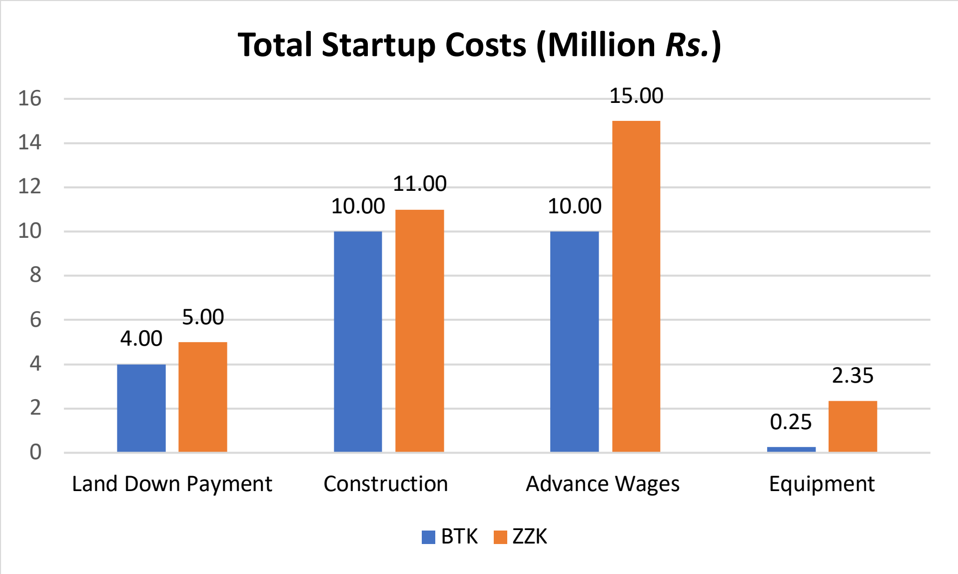

Figure 2: Total startup capital costs

Note: Not shown in the figure is the investment worth *Rs.* 2.5 million (on average) in the initial stock of green bricks at both kilns.

Figure 3 shows the normalized annual total operating costs (total variable costs plus total fixed costs) in *Rs.* per brick of the two kilns. The total operating costs have been normalized by the number of bricks produced to account for the differential size and production capacity of the kilns—the ZZK and BTK produce on average 12 million and 10 million bricks per year, respectively. The fixed costs consist of yearly land lease payments. The variable costs include expenditures on variable factors of production such as fuel (coal), electricity, and raw material (clay and sand). These also include daily wages for workers hired to meet labor demand—the kilns require more workers than those hired on advanced wages. Both kilns use coal as fuel, which constitutes their largest expense. The ZZK consumes higher quality—and therefore more expensive—coal compared to the BTK. However, the ZZK consumes about 33 percent less coal than the BTK owing to its high fuel-efficiency. The lower consumption of coal mostly offsets the expense on high quality coal.

Both kilns use electricity to power tubewells, which provide water to mold clay and sand into green bricks, while the ZZK consumes further electricity to run its draft fan. During power outages, the ZZK shifts to a diesel-powered generator to operate the fan. The ZZK's expenditure on raw materials is higher than the BTK's since it produces more bricks. The ZZK's maintenance costs are also higher given the range of machinery installed in it. Owing to the ZZK's greater startup costs and expenditures on variable factors of production, its total initial year costs are 18 percent higher than those of the BTK. However, given that the ZZK produces

20 percent more bricks than the BTK annually, its total annual operating costs per brick are 9 percent lower.

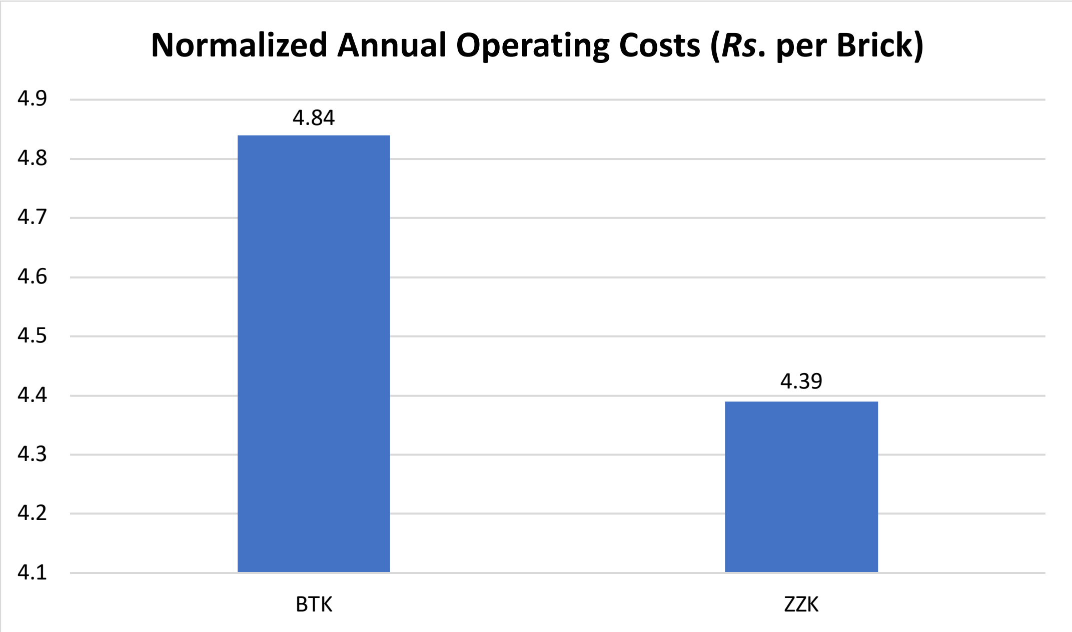

Figure 3: Normalized annual total operating costs

Note: Total operating costs comprise total variable costs and total fixed costs.

3.2. Private Benefits

Kilns produce four grades of bricks, termed, in descending order of quality, Grade A, Hard Brick, Grade B, and Grade C. Brick quality depends on the evenness and consistency of firing, with low-quality bricks being under- or over-burned owing to nonuniform temperatures in the kilns. The highest quality (Grade A) bricks have the most commercial value and fetch *Rs.* 7,000 per thousand—the unit price falls by *Rs.* 1,000 per thousand for each grade reduction.

Figure 4 shows the percentage of each grade of bricks produced by our sample ZZK and BTK. For a fixed amount of bricks baked across the two kilns, the ZZK produces 25 percent more Grade A bricks than the BTK. Since the ZZK produces 20 percent more bricks per year compared to the BTK, it also produces more Grade A bricks in absolute terms—70 percent more than the BTK. This allows the ZZK to generate a larger annual revenue and double the profit as shown in Figure 5, making it more economically attractive than the BTK for private kiln owners.

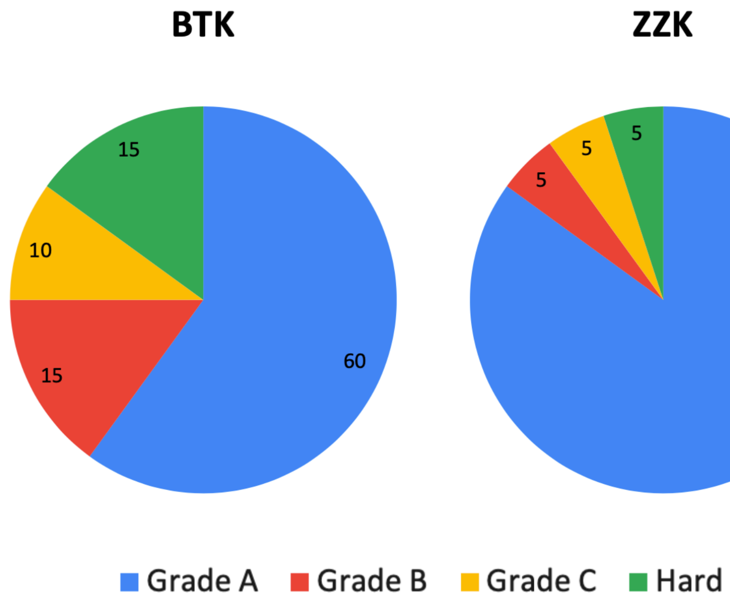

Figure 4: Percentage share of different quality bricks in total production

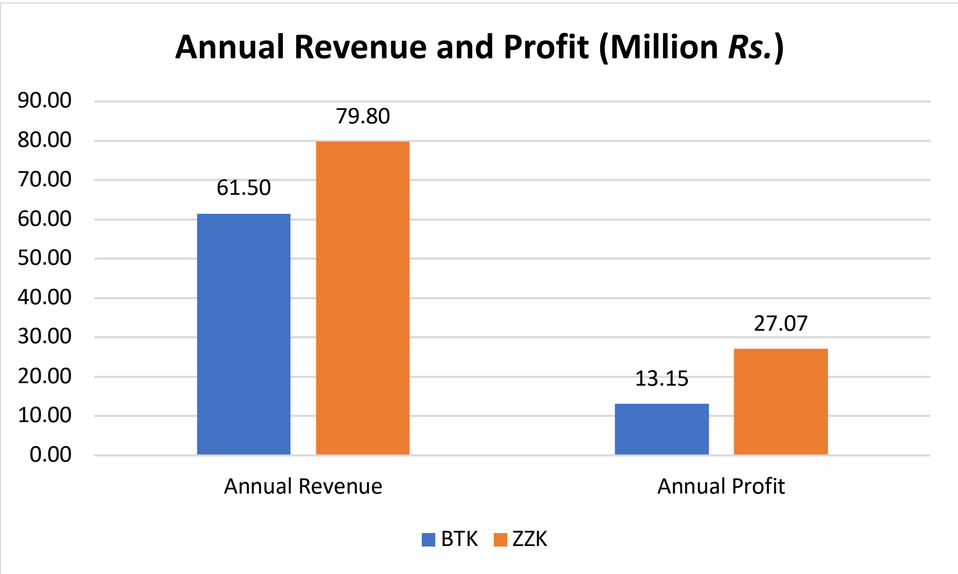

Figure 5: Annual revenue and profit

3.3. Payback Period

Table 6 shows the payback period for the BTK and the ZZK at different real (inflation-adjusted) discount rates. The ZZK's annual profits are more than double (106 percent) the annual profits of the BTK, allowing the owners of the ZZK to recover their initial investment in a shorter period—1.5 years versus 2.4 years under a 10 percent discount rate. The difference between the payback periods of the two kilns becomes larger as the discount rate increases. The profit margins of the two kilns are high enough that owners can recover their initial investments within 2.5 years with a 10 percent discount rate.

Table 6: Discounted Payback Period

Discount Rate (Percent)	Payback Period (Years)	
	BTK	*ZZK*
0.00	2.03	1.33
2.00	2.10	1.36
5.75	2.24	1.43
10.00	2.40	1.50

Note: We have calculated the payback periods using constant cash flows—they do not include depreciation costs. The real interest rate in Pakistan at the time when we conducted our analysis was 5.75 percent—the third choice of the discount rate in the table.

3.4. Cost of CO_2 Emissions

The BTK and the ZZK emit considerable amounts of CO_2 as shown by the preceding environmental analysis. The cost of CO_2 emissions—evaluated using the average price of CO_2 emissions observed in international trading markets—of each kiln provides an approximation of its social cost. In the absence of international prices of the other pollutants, the implicit costs of the other pollutants could not be sufficiently approximated. Therefore, the total costs of CO_2 emitted by each kiln gives a lower bound of their total social costs.

Table 7 shows the calculated values of CO_2 emissions and their costs for each kiln. The BTK's CO_2 emissions are 2.5 times those of the ZZK—14,447 t versus 5,714 t. This translates into present value (with a 10 percent discount rate and a 20-year time horizon) CO_2 emission costs of $Rs.$ 7.42 per brick for the ZZK and $Rs.$ 22.37 per brick for the BTK—the ZZK's social cost per brick is a third that of the BTK.

Table 7: Annual Cost of CO_2 Emissions

	ZZK	BTK
Total brick production ($million\ bricks$)	12	10
CO_2 emission rate (g/h)	652,251	1,649,172
Annual CO_2 emissions (t)	5,714	14,447
Annual CO_2 emissions per brick ($t/100{,}000\ bricks$)	47.60	144.50
Price of CO_2 emissions ($\$/t$)	14.69	14.69
Annual cost of CO_2 emissions ($)	83,939	212,226
Annual cost of CO_2 emissions ($Rs.$)	9,296,244	23,504,030
Annual cost of CO_2 emissions per brick ($\$/brick$)	0.007	0.021
Annual cost of CO_2 emissions per brick ($Rs./brick$)	0.77	2.35
Discount rate (percent)	10.00	10.00
Present value cost of CO_2 emissions ($\$/brick$)	0.067	0.202
Present value cost of CO_2 emissions ($Rs./brick$)	7.42	22.37

Note: The CO_2 emission rate comes from the preceding environmental analysis. The annual CO_2 emissions have been calculated from the CO_2 emission rate by assuming that the kilns operate 24 hours all year round. The Price of CO_2 is in 2017 dollars. An exchange rate of 1$ =110.75 $Rs.$ was used to convert dollar values into rupee values—this was the applicable exchange rate at the time of the analysis. The present value calculations are for a 20-year time horizon.

3.5. Private and Social Benefits

Table 8 shows the discounted costs and benefits of the two types of kilns calculated at a 10 percent discount rate and a 20-year time horizon. The total private costs include the startup capital cost and the annual variable and fixed costs. The total social costs represent the monetary costs of CO_2 emissions. The total private net benefits are equal to the difference between the total benefits (yearly revenue) and the total private costs while the total social net benefits represent the difference between the total private net benefits and the total social costs.

Table 8: Discounted Costs and Benefits

Costs and Benefits ($Million\ Rs.$)	ZZK	BTK
Startup Capital Costs	35.85	26.75
Operating Costs (Fixed and Variable Costs)	501.46	459.81
CO_2 Emissions Costs	88.41	223.52
Total Benefits (Total Revenue)	758.90	584.87
Private Net Benefits	221.59	98.31
Social Net Benefits	133.18	-125.21

Note: The present value calculations are for a 20-year time horizon.

The results show that the ZZK's total private net benefits are more than twice those of the BTK over a 20-year period. The ZZK also generates significant total social net benefits while the BTK's total social costs exceed its total private net benefit, leading to a considerable social loss (negative total social benefits) over the 20-year time horizon. The ZZK's private net benefits and social net benefits are $Rs.$ 221.59 million and $Rs.$ 133.18 million, respectively, compared to $Rs.$ 98.31 million and $Rs.$ -125.21 million for the BTK. The figures for the total social costs are lower bounds for the actual values since they exclude costs of the emissions of other harmful pollutants. The perceived social benefits of the ZZK would be even higher given that it emits lower amounts of SO_2, CO, and PM than the BTK.

Table 9 shows the total private benefits and the total social costs for each kiln under different discount rates. The absolute difference and the relative (proportional) difference between the total social benefits of the two kilns are larger at lower discount rates. The results provide strong evidence that the adoption of ZZK technology would monetarily enhance social welfare.

An important caveat here is that the differences in returns across the two kilns are possibly correlated with managerial and operational practices. Improved fuel feeding practices could increase the fuel efficiency of BTKs and therefore lower emissions and lead to better private and social returns. Moreover, the study focuses on the private and social benefits of new ZZKs. Retrofitting exiting BTKs is a cheaper alternative to constructing and operationalizing new ZZKs. The conversion of existing BTKs into ZZKs precludes fixed expenditures on land acquisition and construction, which translates into savings worth over 90 percent of the fixed costs of constructing a new ZZK. From a policy perspective, retrofitting BTKs with ZZK technology offers a more practical and feasible option to incentivizing ZZKs than new construction from the ground up.

Table 9: Private and Social Net Benefits under Various Discount Rates

	Private Net Benefits ($Million\ Rs.$)		Social Net Benefits ($Million\ Rs.$)	
Discount Rate (Percent)	**ZZK**	**BTK**	**ZZK**	**BTK**
2.00	433.81	201.40	272.52	-206.39
5.75	308.21	140.39	190.05	-158.35
10	221.59	98.31	133.18	-125.21

Note: 2—10 percent represents the range within which Pakistan's real interest rate has fluctuated in the last ten years. 5.75 percent was Pakistan's average real interest rate at the time of the analysis. The present value calculations are for a 20-year time horizon.

4. Conclusion, Limitations, and Recommendations

The environmental and economic comparison of two different kiln technologies—ZZK and BTK—in this study demonstrates that the ZZK is considerably more environmentally friendly and socially cost-effective than the BTK. The sampled ZZK emitted far lower amounts of sulfur dioxide, carbon dioxide, carbon monoxide, and particulate matter compared to the BTK. The ZZK produces more high-quality bricks and combusts coal more efficiently than the BTK, which translates into higher private net benefits for ZZK owners. The higher private net benefits allow ZZK owners to recover their startup capital costs in less than two years—compared to 2.4 years for BTK owners. Since the ZZK also emits lower amounts of pollutants and greenhouse gases, it generates considerably higher social returns than the BTK. This provides strong evidence for encouraging kiln owners to shift from BTKs to ZZKs.

The results should be taken with a hint of caution. Though the study followed the US Environmental Protection Agency's recommended procedures to monitor emissions, the sample included one kiln of each type of technology. Since fuel type, fuel quality, and operating conditions vary across kilns, monitoring of a larger sample of kilns would provide more representative results. Moreover, emissions at each kiln were monitored for a short duration during daytime, ignoring the variation in emissions during nighttime. A 24-hour monitoring regimen would more accurately identify the diurnal variation in the emissions of each kiln. Lastly, the study—as well as most others in the literature—relied on measurements of flue emissions. As Chen et al. 2017 point out, ignoring fugitive emissions that result through cracks in the furnace roof and the fuel feeding holes will underestimate the actual emissions. Monitoring of both flue and fugitive emissions will provide a better portfolio of emissions from different kiln technologies.

The ZZK presents a potential opportunity for developing countries to improve their ambient air quality in a cost-effective manner. Using regional networks, demonstration sights, regular informational sessions, and basic support, environmental authorities can effectively facilitate kiln owners to construct and operate ZZKs.

Acknowledgments

We would like to thank the International Growth Center (IGC) for funding our research under grant 37419. Ammara Rana, Umair Kiani and Marium Piracha's tireless and impeccable research assistance has been instrumental in the completion of this paper. We acknowledge the staff of the Punjab Environment Protection Department, for facilitating our collaboration with the owners of our sample kilns and for providing logistical support. We are thankful to Mr. Muhammad Arfan at the Environmental Protection Agency Lab for his technical assistance with emissions monitoring. We appreciate the unconditional support of Mr. Tayab Ikram (owner of the sampled zigzag kiln) and Mr. Muhammad Aslam (owner of the sampled Bull's Trench kiln) during the course of the study.

References

Adrees, M., Ibrahim, M., Shah, A.M., Abbas, F., Saleem, F., Rizwan, M., Hina, S., Jabeen, F. and Ali, S. (2016). "Gaseous pollutants from brick kiln industry decreased the growth, photosynthesis, and yield of wheat (Triticum aestivum L.)." *Environmental Monitoring and Assessment, 188*(5): 267.

Brook, R.D., Franklin, B., Cascio, W., Hong, Y., Howard, G., Lipsett, M., Luepker, R., Mittleman, M., Samet, J., Smith, S.C. and Tager, I. (2004). "Air pollution and cardiovascular disease: a statement for healthcare professionals from the Expert Panel on Population and Prevention Science of the American Heart Association." *Circulation*, 109(21): 2655-2671.

Chen, Y., Du, W., Zhuo, S., Liu, W., Liu, Y., Shen, G., Wu, S., Li, J., Zhou, B., Wang, G., Zeng, E., Cheng, H., Liu, W., Tao, S. (2017). "Stack and fugitive emissions of major air pollutants from typical brick kilns in China." Environmental Pollution, 224: 421-429.

Colbeck, I., Nasir, Z., and Ali, Z. (2009). "The state of ambient air quality in Pakistan-a review." Environmental Science and Pollution Research International, 17: 49-63.

Croitoru, L. and Sarraf, M. (2012). "Benefits and costs of the informal sector: the case of brick kilns in Bangladesh." *Journal of Environmental Protection* 3(6): 476-484.

Dominici, F., Peng, R. D., Bell, M. L., Pham, L., McDermott, A., Zeger, S. L., and Samet, J. M. (2006). "Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases." Jama 295(10): 1127-1134.

EPD (Environmental Protection Department, Punjab). (2017). *Monitoring of Air Quality of Lahore*. Lahore: Environmental Protection Department, Punjab.

HEI (Health Effects Institute). (2017). State of Global Air 2017. Special Report. Boston, MA: Health Effects Institute.

Gilliland, F.D., Berhane, K., Rappaport, E.B., Thomas, D.C., Avol, E., Gauderman, W.J., London, S.J., Margolis, H.G., McConnell, R., Islam, K.T. and Peters, J.M. (2001). "The effects of ambient air pollution on school absenteeism due to respiratory illnesses." *Epidemiology 12*(1): 43-54.

ICIMOD (International Center for Integrated Mountain Development). (2019). South-South business partnerships towards energy-efficient and low-emission brick production in Pakistan. http://www.icimod.org/?q=35117 (accessed 20 November 2019).

Ismail, M., Muhammad, D., Khan, F., Munsif, F., Ahmad, T., Ali, S. (2012). "Effect of brick kilns emissions on heavy metal (Cd and Cr) content of contiguous soil and plants." Sarhad Journal of Agriculture, 28: 403–409.

Jayarathne, T., Stockwell, C.E., Bhave, P.V., Praveen, P.S., Rathnayake, C.M., Islam, M.R. Panday, A.K., Adhikari, S., Maharjan, R. Goetz, J.D., DeCarlo, P.F., Saikawa, E., Yokelson, R.J., Stone, E.A.

(2018). "Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE): emissions of particulate matter from wood and dung-fueled cooking fires, garbage and crop residue burning, brick kilns, and other sources." Atmospheric Chemistry and Physics, 18: 2259–2286.

Kamal, A., Malik, R. N., Martellini, T., and Cincinelli, A. (2014). "Cancer risk evaluation of brick kiln workers exposed to dust bound PAHs in Punjab province (Pakistan)." Science of The Total Environment, 493:562-570.

Khan, A., Blaschke, T., Madl, P., Mukhtar, A., Hussain, M., Trautmann, T., Rahman, S. (2011). "Aerosol size distribution and mass concentration measurements in various cities of Pakistan." Journal of Environmental Monitoring, 13(7): 1944-52.

Lodhi, Z. (2006). Ambient Air Quality in Pakistan. Pakistan Environmental Protection Agency.

Maithel, S., Kumar, S., and Lalchandani, D. (2014). *Factsheets about brick kilns in South and Southeast Asia*. New Delhi: Greentech Knowledge Solutions Pvt. Ltd.

Mondal, A., Das, S., Sah, R.K., Bhattacharyya, P., Bhattacharya, S.S. (2017). "Environmental footprints of brick kiln bottom ashes: Geostatistical approach for assessment of metals toxicity." Science of the Total Environment, 609: 215-224.

Malik, N. (2016). "Bonded Labour in Pakistan". Advances in Anthropology 6: 127-136.

Nepal, S., Mahapatra, P.S., Adhikari, S., Shrestha, S., Sharma, P., Shrestha, K.L., Pradhan, B.B. and Puppala, S.P. (2019). "A Comparative Study of Stack Emissions from Straight-Line and Zigzag Brick Kilns in Nepal." *Atmosphere*, *10*: 107.

Rajarathnam, U., Athalye, V., Ragavan, S., Maithel, S., Lalchandani, D., Kumar, S., Baum, E., Weyant, C., Bond, T. (2014). "Assessment of air pollutant emissions from brick kilns." Atmospheric Environment, 98:549-553.

Sager, L. (2016). "Estimating the effect of air pollution on road safety using atmospheric temperature inversions." Grantham Research Institute on Climate Change and the Environment Working Paper 251, London School of Economics, London, UK.

Sanjel, S., Thygerson, S.M., Khanal, S.N. and Joshi, S.K. (2016). "Environmental and Occupational Pollutants and Their Effects on Health among Brick Kiln Workers." Open Journal of Safety Science and Technology, 6: 81-98.

Skinder, B. M., Sheikh, A. Q., Pandit, A. K., and Ganai, B. A. (2014). "Brick kiln emissions and its environmental impact: A Review." Journal of Ecology and The Natural Environment, 6(1):1-11.

Stockwell, C.E., Christian, T.J., Goetz, J.D., Jayarathne, T., Bhave, P.V., Praveen, P.S., Adhikari, S., Maharjan, R., Decarlo, P.F., Stone, E.A., Saikawa, E., Blake, D.R., Simpson, I., Yokelson, R.J., Panday, A.K. (2016). "Nepal ambient monitoring and source testing experiment (NAMaSTE): Emissions of trace gases and light-absorbing carbon from wood and dung cooking fires, garbage and crop residue burning, brick kilns, and other sources." Atmospheric Chemistry and Physics, 16: 11043–11081.

Tahir, S. N. A., Rafique, M., and Alaamer, A. S. (2010). "Biomass fuel burning and its implications: deforestation and greenhouse gases emissions in Pakistan." Environmental Pollution, 158(7): 2490-2495.

Tehzeeb, A.H. and Bhuiyan, M.A. (2014). "Operation of Brick Kilns in Bangladesh–A Comparative Study." *Asian Journal of Water, Environment and Pollution*, 11(2): 55-65.

US EPA. (2017). Method 17: Determination of particulate matter emissions from stationary sources. US EPA: Washington DC.

US EPA. (2017). Method 2: Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube). US EPA: Washington DC.

Weyant, C., Athalye, V., Ragavan, S., Rajarathnam, U., Lalchandani, D., Maithel, S., Baum, E., Bond, T.C. (2014). "Emissions from South Asian brick production." Environmental Science and Technology, 48: 6477−6483.

Zavala, M., Molina, L.T. Maiz, P., Monsivais, I., Chow, J.C., Watson, J.G., Munguia, J.L., Cardenas, B., C. Fortner, E.C., Herndon, S.C., Roscioli, J.R. Kolb, C.E., Knighton, W.B. (2018). "Black carbon, organic carbon, and co-pollutant emissions and energy efficiency from artisanal brick production in Mexico." Atmospheric Chemistry and Physics, 18: 6023–6037.

Appendix

A1. Brick Kiln Technologies

This section provides a brief description of BTKs and ZZKs followed by an overview of alternative kiln technologies in South Asia.

A1.1. Bull's Trench Kiln

Invented in Bengal in 1876 by the British engineer William Bull, the BTK is the most widely used kiln technology across Pakistan (and South Asia). A well-functioning BTK produces 50,000 bricks a day on average. The kiln comprises a large circular structure called the chamber—in which workers place "green bricks" (sun-dried clay molds) for firing—with a fixed chimney, 20 – 30 m high, in its center that allows a natural draft through the structure and discharges flue gases.

The chamber has three zones: firing zone; preheating zone; cooling zone. Combustion occurs in the firing zone, producing flue gases that flow forward to the preheating zone and preheating the next batch of green bricks. The cooling zone, placed behind the firing zone, is where the fresh draft through the kiln cools the fired bricks.

The production process in a BTK begins with workers placing a stack of green bricks in the firing zone where it bakes in a continuously burning fire, which moves in a circular circuit through the chamber by following the flow of the draft provided by the chimney. Workers sustain the fire by adding fuel through feeding holes on top of the chamber every 15 to 20 minutes. Workers cover the bricks in the chamber with ash and brick dust to increase insulation and prevent heat loss. Once the fire sufficiently fires the bricks, it moves forward while cool air from the back of the chamber cools the bricks. To guide the flue gases towards the chimney, workers seal the front of the preheating zone. Finally, workers remove the cooled bricks from the front of the cooling zone and replace it with new bricks and the process repeats.

A1.2. Induced Draught Zigzag Kiln (ICIMOD Design)

The structure of a ZZK is almost identical to that of a BTK except it has a slightly shorter chimney and an electric fan installed in the vent to control the flow of the draft through the chamber.[1] In a ZZK, workers place green bricks in a diagonal fashion, which forces the draft to follow a longer zigzag path—hence the name Zigzag Kiln—through the chamber. This longer path taken by the draft increases the airflow in the chamber, leading to more efficient fuel combustion compared to a BTK. It also transfers greater heat from the firing zone to the pre-heating zone, allowing more consistent firing of bricks.

[1] The ZZK structure described here is based on a design by the International Center for Integrated Mountain Development (ICIMOD). The details of the design (including figures) can be found in: MinErgy Private Limited and the Federation of Nepalese Brick Industries. (2015). Design Manual: Improved Fixed Chimney Brick Kiln. ICIMOD Technical Report.

Figure A1: (a) Fuel feeding at the BTK, (b) Fuel feeding at the ZZK, (c) Stacked green and fired bricks at the ZZK, (d) Horbia PG-350E used for measuring stack gaseous emissions.

A2. Monitoring of Stack Emissions

Measurements of stack gaseous and PM concentrations are given in Table A1 while their averages are shown in Figure A2. Results showed that SO_2 (mg/m^3) and CO (mg/m^3) emissions were significantly higher than their Punjab Environmental Quality Standards (PEQS) 2016 values during feeding period of BTK. While these emissions remained lower than PEQS values at ZZK and non-feeding cycle of BTK. NOx (mg/m^3) emissions were much lower than the PEQS value (1200) for both kilns. PEQS limits for SO_2, CO and PM were only exceeded during feeding cycle of BTK while values of NO_x for both kilns were much lower than the standard values. High PM concentration in the stack emissions of BTK during feeding is also reflected in its black smoke while the smoke of ZZK was white almost all the times and rarely did it appear greyish.

Table A1: Measurements of stack concentrations

No.	BTK Feeding (F) and Non-Feeding (NF)										ZZK				
	CO_2 (mg/m^3)		SO_2 (mg/m^3)		NO_x (mg/m^3)		CO (mg/m^3)		PM (mg/m^3)		CO_2 (mg/m^3)	SO_2 (mg/m^3)	NO_x (mg/m^3)	CO (mg/m^3)	PM (mg/m^3)
	F	NF	F	NF	F	NF	F	NF	F	NF					
1	100417	38151	2741	102	15.68	7.53	2870	362	1464.7	333	18716	10	11	158	17
2	175820	53448	9621	277	28.22	9.41	7127	496	390	12	59746	105	36	540	
3	187337	51648	12474	314	33.24	9.41	7792	464			58307	204	37.6	602	
4	167302		7625		30.73		4772				53268	215	36	574	
5	124052		2198		25.09		1503								
6	98558		1058		18.81		944								
Average	142248	47749	5953	231	25.29	8.78	4168	440	927	172.5	47509	134	30.15	469	17
Time-weighted average	79249		2138		14.28		1683		424						

Note: The BTK's average feeding cycle and average non-feeding cycle are 15 mins and 30 mins, respectively.

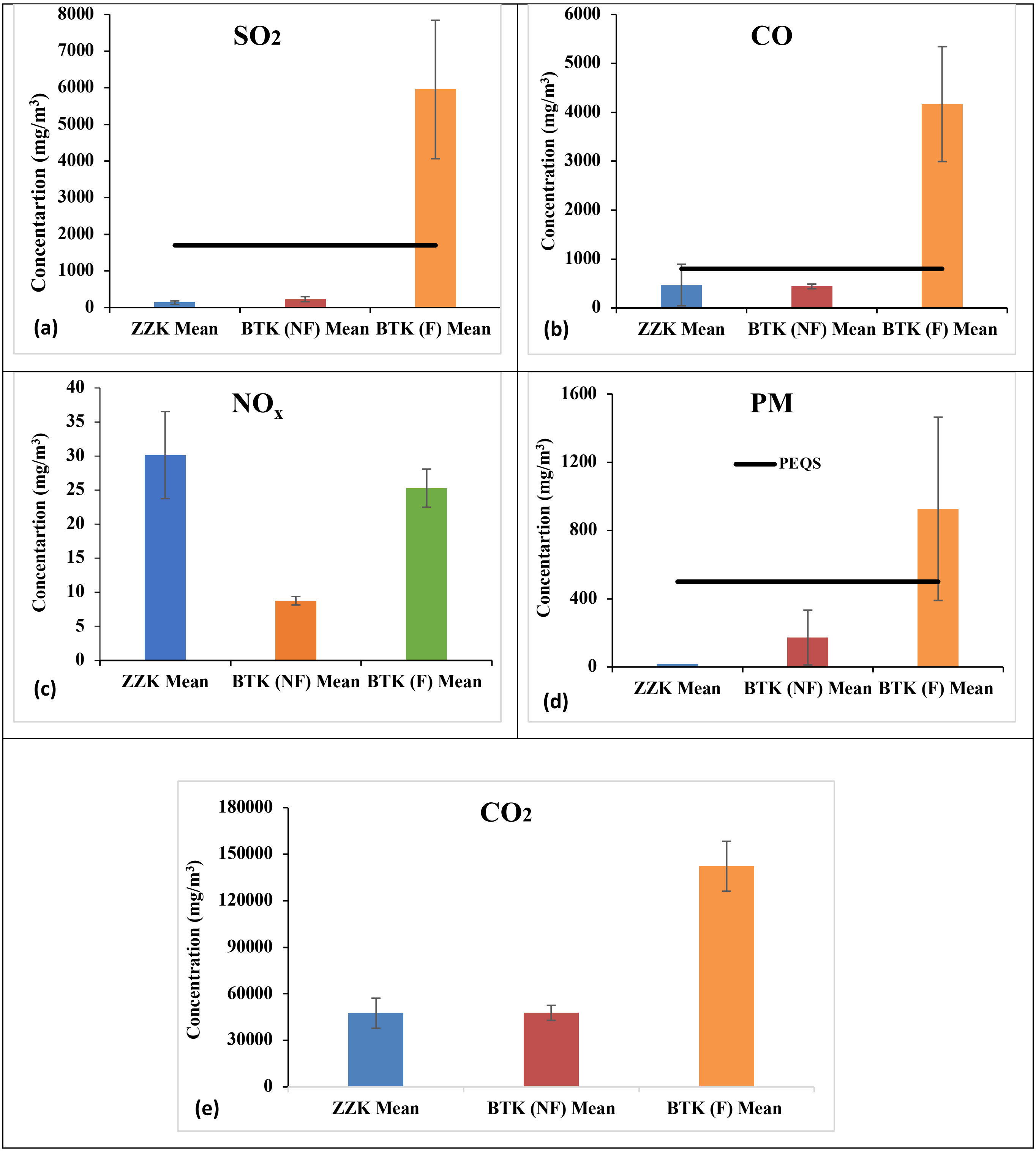

Figure A2: Comparison of stack emissions (mg/m^3) of (a) SO_2, (b) CO, (c) NO_x, (d) PM and (e) CO_2 of the sampled ZZK and BTK with their respective PEQS.
F = feeding; NF = non-feeding.

A3. Emission Rate Comparison

Comparison of CO emission rates (g/min) show the lowest value for ZZK of the current study while this value was much higher for traditional fixed kiln in Zavala et al. (2018) where wood and diesel were used as fuel (Table A2). All other emission rates also followed same trend except for SO_2 where these values were much higher for the current study because of high Sulphur contents of the coal.

Table A2: Comparison of emission rates (g/min) estimated in this study with other study

	Zavala at el. (2018)			Current study	
Kiln type	**MK2**	**Traditional campaign**	**Traditional fixed**	**BTK**	**ZZK**
Fuel	**Wood**	**Wood**	**Wood, diesel, sawdust**	**Coal**	**Coal**
CO_2	-	-	-	27486	10871
CO	270.7	553.7	8500.2	584	107
NO_x	7.4	7.8	53.8	4.95	6.9
SO_2	3.6	1.1	8.7	742	30.55
PM	3.9	17.5	171.9	147	3.89